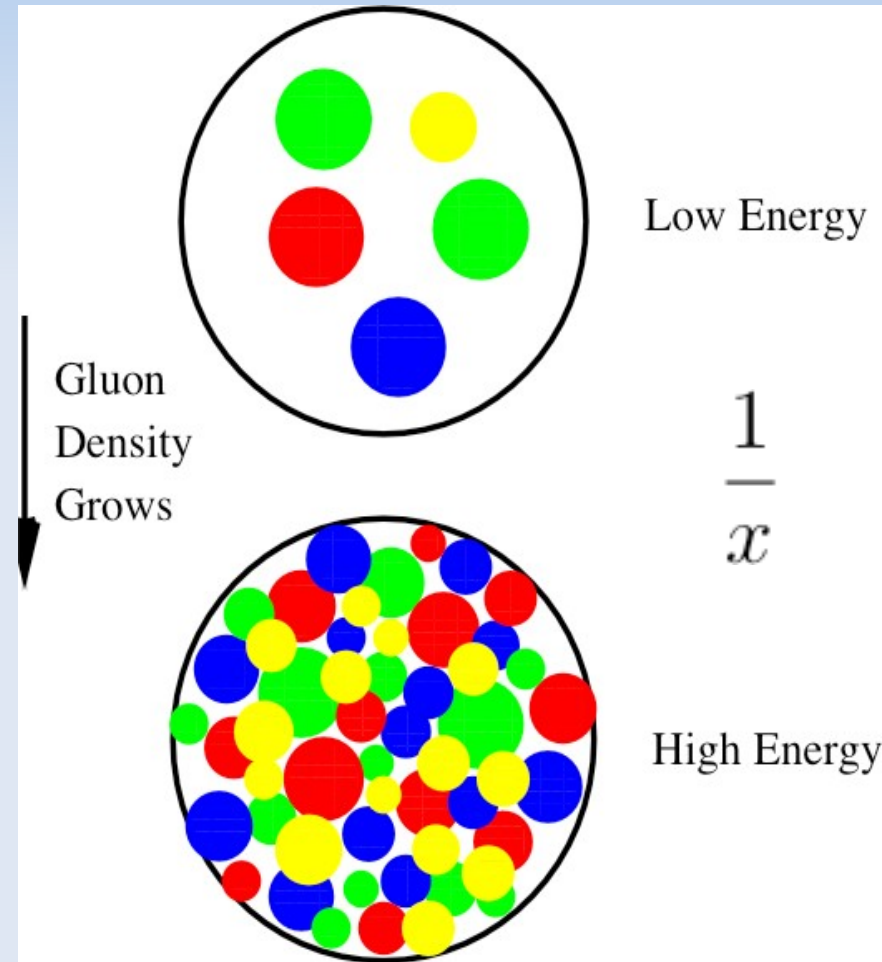
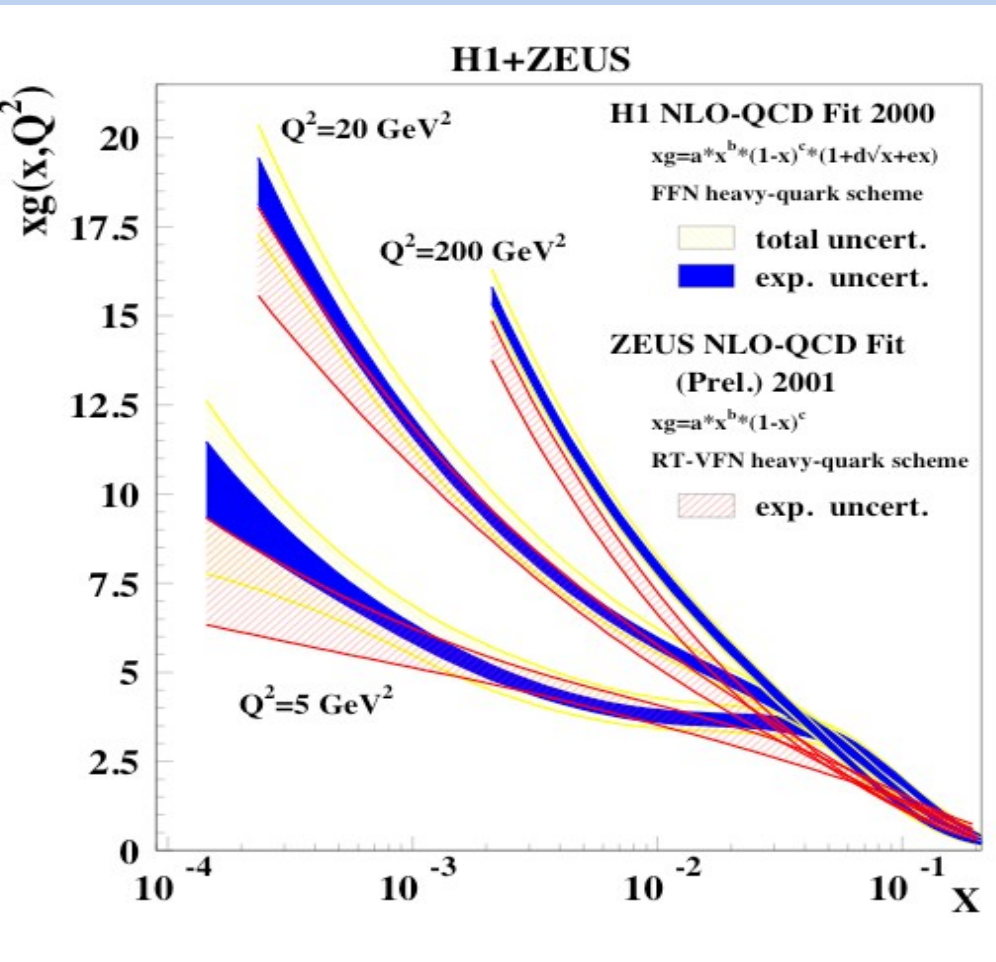


Photon-Hadron Correlations in dA Collisions and Saturation Physics

Jamal Jalilian-Marian
Baruch College
New York, NY

Saturation



Mechanism for parton saturation

**Competition: “attractive” bremsstrahlung
vs. “repulsive” recombination effects**

Maximum occupation number =>

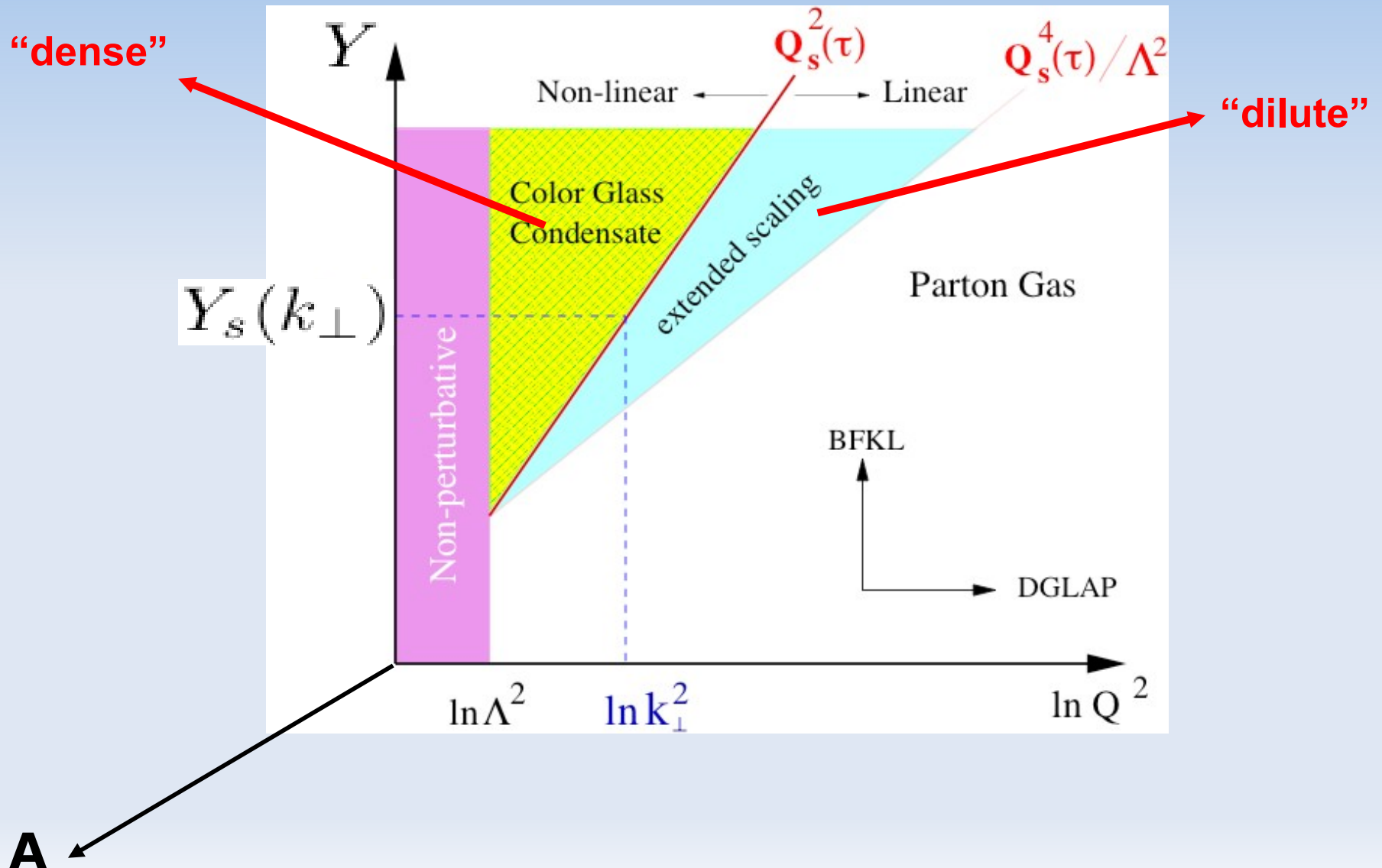
$$\frac{1}{2(N_c^2 - 1)} \frac{x G(x, Q^2)}{\pi R^2 Q^2} = \frac{1}{\alpha_S(Q^2)}$$

saturated for

$$Q = Q_s(x) \gg \Lambda_{\text{QCD}} \simeq 0.2 \text{ GeV}$$

$$Q_s^2(x, A) \sim A^{1/3} \left(\frac{1}{x}\right)^{0.3}$$

Road Map of QCD



Color Glass Condensate

An effective action which includes:

high gluon density: “multiple scatterings”

high energy : evolution with $1/x$

effective degrees of freedom: Wilson lines

B-JIMWLK: evolution of n-point functions

$$\frac{\partial}{\partial y} \langle \mathbf{O}[\mathbf{A}] \rangle = \frac{1}{2} \langle \frac{\delta}{\delta \mathbf{A}^a(\mathbf{x}_t)} \eta_{\mathbf{x}_t, \mathbf{y}_t}^{ab} \frac{\delta}{\delta \mathbf{A}^b(\mathbf{y}_t)} \mathbf{O}[\mathbf{A}] \rangle$$

BK: mean field + large N_c

$$\langle \text{Tr} V^\dagger V \dots V_{2n} \rangle = \langle \text{Tr} V^\dagger V \rangle^n$$

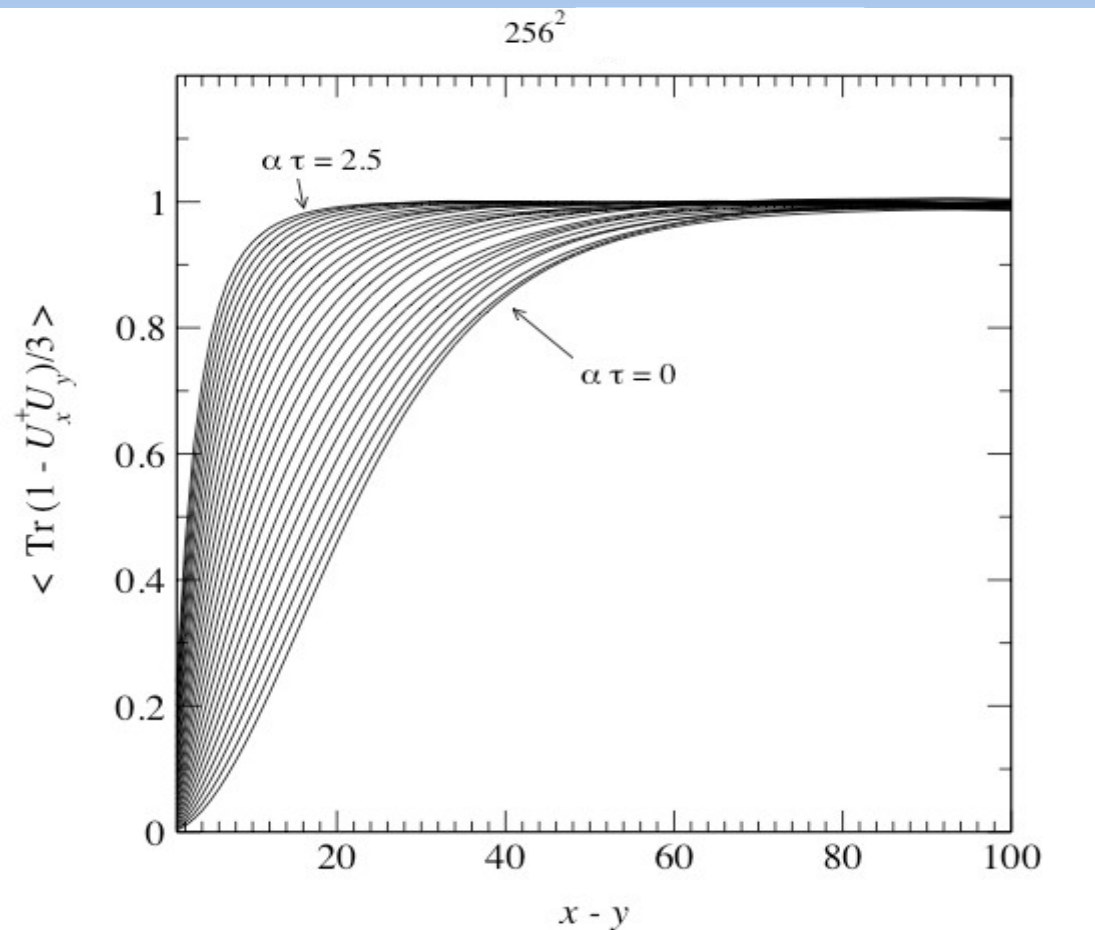
where

$$\frac{1}{N_c} \langle \text{Tr} [1 - V^\dagger(\mathbf{x}_t) V(\mathbf{y}_t)] \rangle \equiv N_F(\mathbf{x}_t - \mathbf{y}_t)$$

$$\frac{d}{dy} N_F(\mathbf{x}_t - \mathbf{y}_t) = \frac{\bar{\alpha}_s}{2\pi} \int d^2 \mathbf{z}_t \frac{(\mathbf{x}_t - \mathbf{y}_t)^2}{(\mathbf{x}_t - \mathbf{z}_t)^2 (\mathbf{y}_t - \mathbf{z}_t)^2} \times$$

$$[N_F(\mathbf{x} - \mathbf{z}) + N_F(\mathbf{z} - \mathbf{y}) - N_F(\mathbf{x} - \mathbf{y}) - N_F(\mathbf{x} - \mathbf{z}) N_F(\mathbf{z} - \mathbf{y})]$$

The two point function (dipole cross section)



$$N_F(\mathbf{p}_t) \rightarrow \frac{1}{p_t^2} \log \left[\frac{Q_s^2}{p_t^2} \right]$$

$$N_F(\mathbf{p}_t) \rightarrow \frac{1}{p_t^2} \left[\frac{Q_s^2}{p_t^2} \right]^\gamma$$

$$N_F(\mathbf{p}_t) \rightarrow \frac{1}{p_t^2} \left[\frac{Q_s^2}{p_t^2} \right]$$

KR+HW, NPA739 (2004) 183
 NLO: B-BC-KW (2007-2008)

Signatures of CGC at RHIC

- ✓ Multiplicities (dominated by $p_+ < Q_s$):
energy, rapidity, centrality dependence
- Single particle production: hadrons, photons, dileptons
rapidity, p_+ , centrality dependence
- Fixed p_+ : vary rapidity (evolution in x)
- Fixed rapidity: vary p_+ (transition from dense to dilute)

***Two particle production:
correlations***

Single inclusive hadron production in pA

$$\frac{d\sigma^{pA \rightarrow hX}}{dY d^2 P_t d^2 b} = \frac{1}{(2\pi)^2} \int_{x_F}^1 dx \frac{x}{x_F} \left\{ f_{q/p}(x, Q^2) N_F\left[\frac{x}{x_F} P_t, b, y\right] D_{h/q}\left(\frac{x_F}{x}, Q^2\right) + f_{g/p}(x, Q^2) N_A\left[\frac{x}{x_F} P_t, b, y\right] D_{h/g}\left(\frac{x_F}{x}, Q^2\right) \right\}$$

ONLY 2-POINT FUNCTIONS APPEAR

Same as in DIS and photon, dilepton production

The dipole cross section

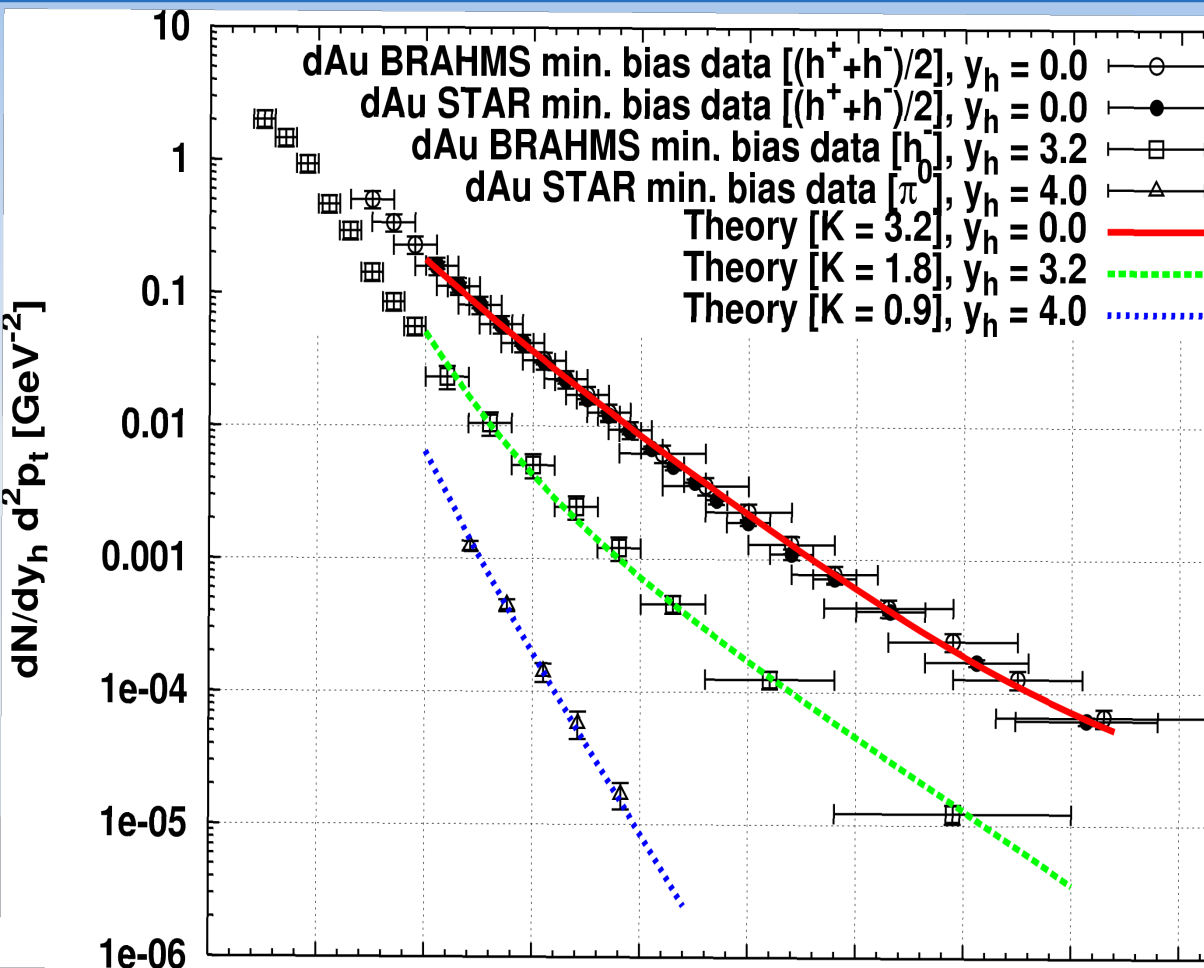
Parameterizations: anomalous dimension

$$N_A(r_t, y_h) = 1 - \exp \left[-\frac{1}{4} (r_t^2 Q_s^2(y_h))^{\gamma(y_h, r_t)} \right]$$

$$\begin{aligned} \gamma_{DHJ}(Q^2, Y) &= \gamma_s + \Delta\gamma(Q^2, Y) \\ \Delta\gamma &= (1 - \gamma_s) \frac{\log(Q^2/Q_s^2)}{\lambda Y + \log(Q^2/Q_s^2) + d\sqrt{Y}} \end{aligned}$$

recently: numerical solution of NLO BK

Single inclusive hadrons in dA



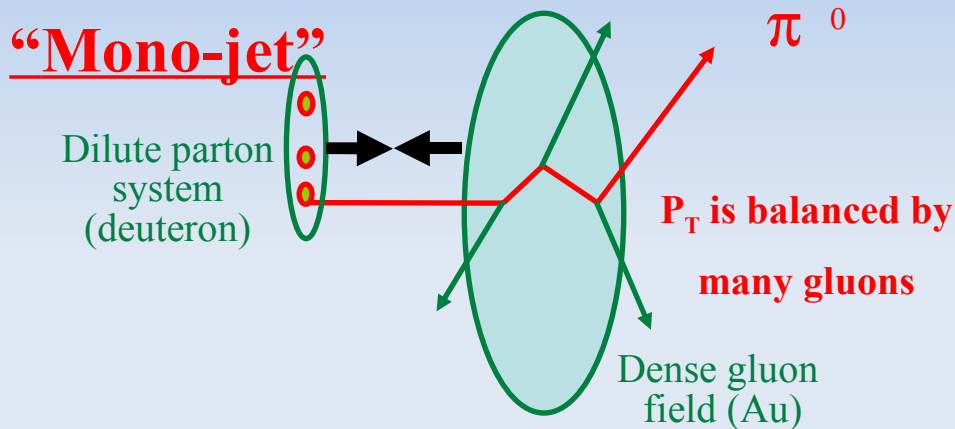
DHJ:NPA770 (2006)
spectrum at $y=4$ was
a true prediction

also
BUW:PRD77 (2008)

AM, arXiv:1001.1378, from numerical solution of NLO BK

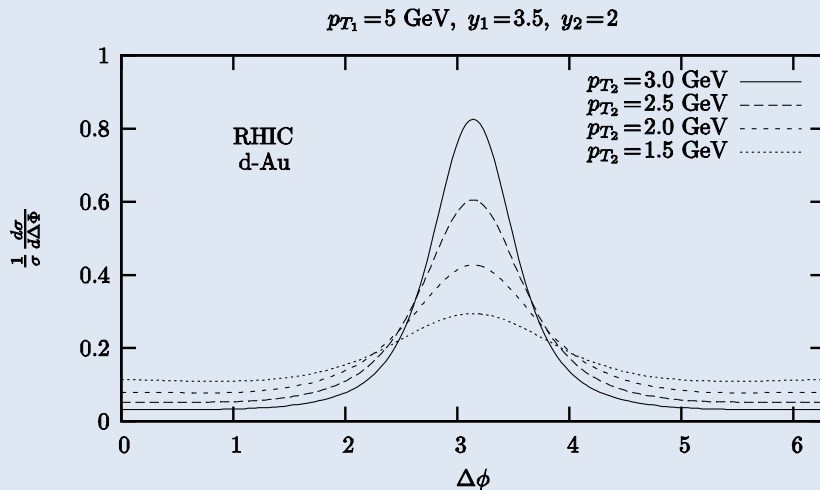
Two particle correlations (away side): dA

disappearance of back to back jets

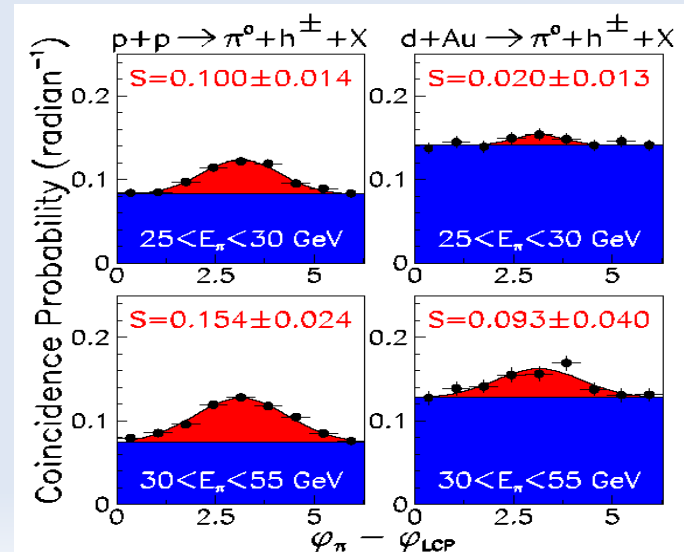


Di-jet vs. mono-jet

KLM, NPA748 (2005) 627



C. Marquet



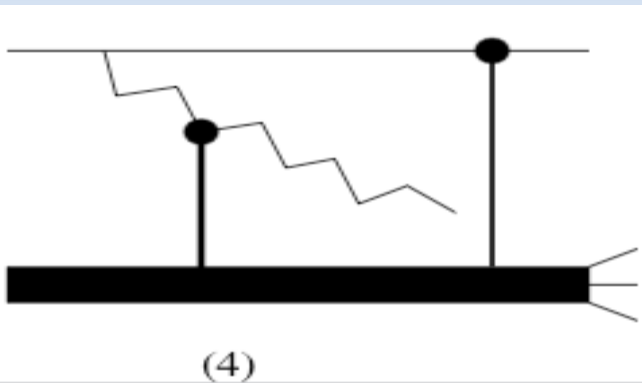
star

Two hadron production:dA

two hadron production probes higher point functions

JJM and YK, PRD70 (2004) 114017

CM, NPA796 (2007) 41



$$|M_4|^2 = 16p^- p^- z(1+z^2) \int \frac{d^2 l_t}{(2\pi)^2} \frac{d^2 \bar{l}_t}{(2\pi)^2} \frac{l_t \cdot \bar{l}_t}{l_t^2 \bar{l}_t^2} \\ [U^{\dagger ac}(k_t - \bar{l}_t) - \delta^{ac}(2\pi)^2 \delta^2(k_t - \bar{l}_t)] \\ [U^{ab}(k_t - l_t) - \delta^{ab}(2\pi)^2 \delta^2(k_t - l_t)] \\ \text{Tr } t^c t^b [V^\dagger(q_t + l_t) - (2\pi)^2 \delta^2(q_t + l_t)] \\ [V(q_t + \bar{l}_t) - (2\pi)^2 \delta^2(q_t + \bar{l}_t)]$$

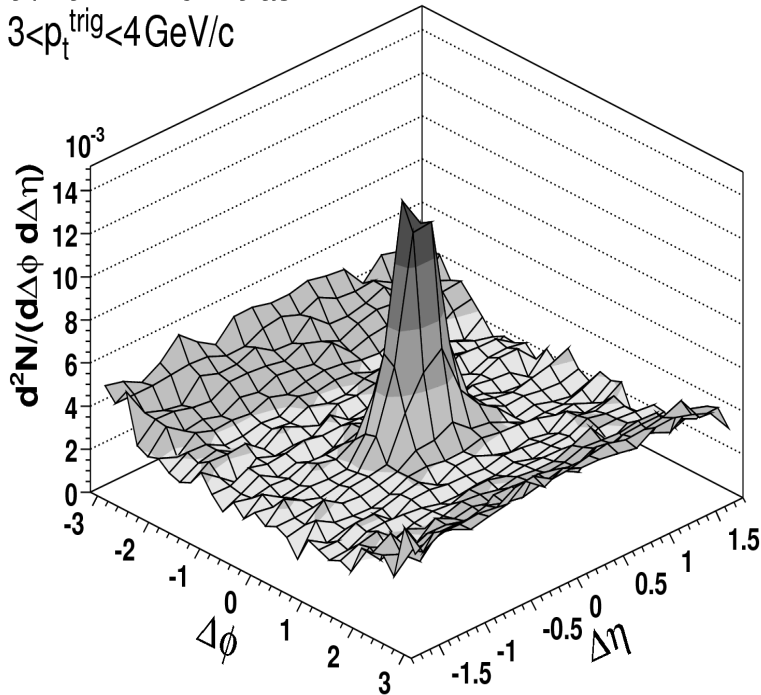
Mean field + large N_c ---> BK for 2-point functions

BK truncation of JIMWLK misses some important contributions (AD+JJM)

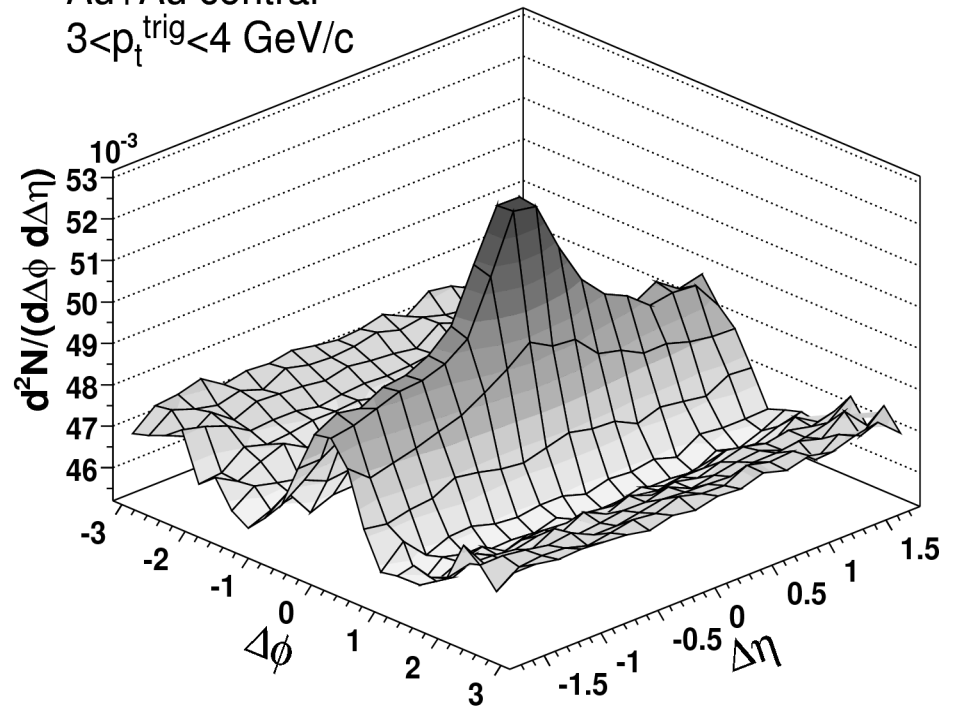
need to solve JIMWLK evolution of n-point functions on lattice

Ridge in AA

d+Au minimum bias
 $3 < p_t^{\text{trig}} < 4 \text{ GeV}/c$



Au+Au central
 $3 < p_t^{\text{trig}} < 4 \text{ GeV}/c$



near-side correlations: $|\Delta\Phi| < 1$

DGMV, NPA810 (2008) 91, this is a CGC effect

Ridge in AA

terms “sub-leading” in N_c contribute at the same order to correlation function

B-JIMWLK in mean field (BK) approximation:

$$\begin{aligned} \langle A^a A^b A^c A^d \rangle = & \delta^{ab} \delta^{cd} \langle A A \rangle^2 \\ & + \frac{1}{N_c} f^{abe} f^{cde} \langle A A \rangle^2 \end{aligned}$$

multiplied by external color factors: both terms are of order

$$N_c^2 (N_c^2 - 1)$$

qualitative behavior should not be affected

A. Dumitru's talk in this workshop

Photon-Hadron correlations: dA

another process to test CGC formalism

less inclusive than single inclusive particle production

one less hadron fragmentation function

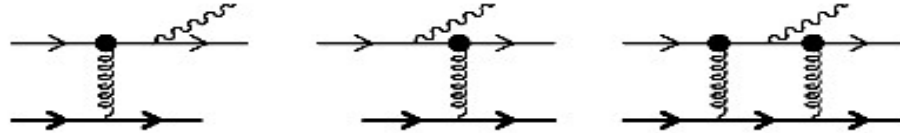
theoretically cleaner: 2-point function only

lower rates compared to two hadron production

photons are hard to measure

will help distinguish between different approaches

$$q(p) \, T \rightarrow q(q) \, \gamma(k) \, X$$



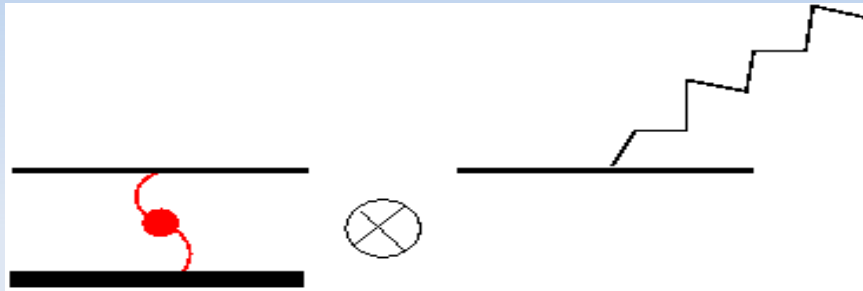
$$\frac{d\sigma^{d \, A \rightarrow h \, \gamma \, X}}{d^2b_t \, dq_t^2 \, dk_t^2 \, dy_\gamma \, dy_h \, d\theta} = a \int_{z_{\min}}^1 \frac{dz}{z^5} f_{q/d}(x_p, Q^2)$$

$$D_{h/q}(z, Q^2) [z^2 + (\frac{q^-}{q^- + zk^-})^2] \frac{(\tilde{q}_t + z\tilde{k}_t)^2}{(k^- \tilde{q}_t - q^- \tilde{k}_t)^2} \mathbf{N_F}(|\tilde{q}_t/z + \tilde{k}_t|)$$

FG-JJM, PRD66 (2002) 014021
 JJM, EPJC61 (2009) 789

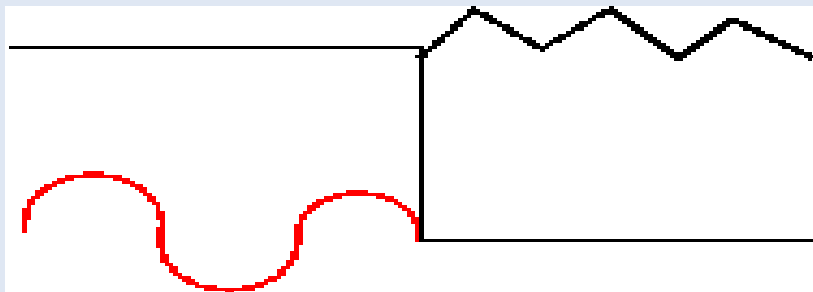
pQCD limit

near side: collinear divergence $\theta \rightarrow 0$



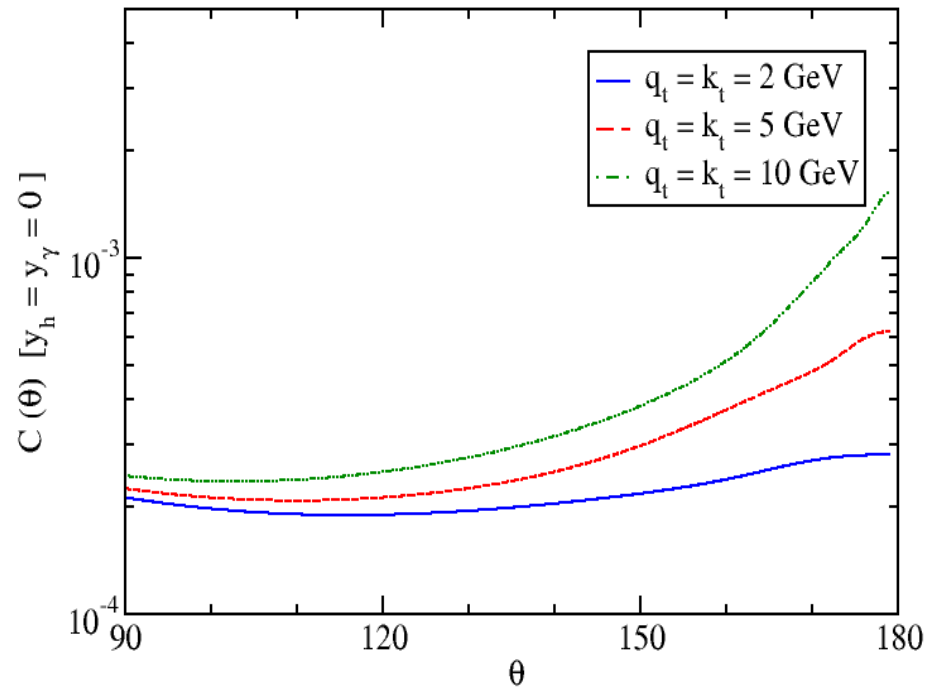
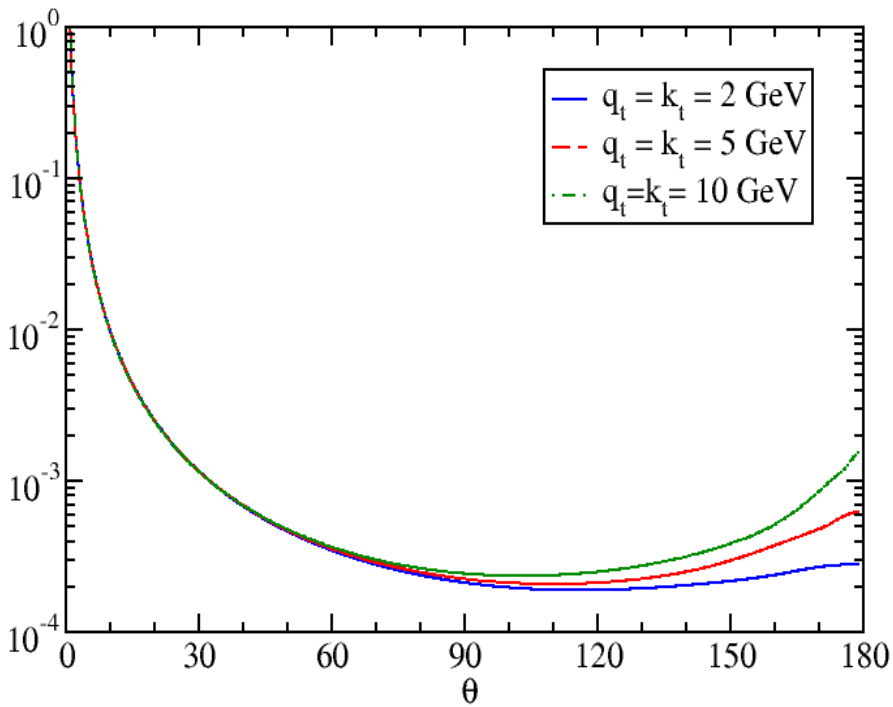
$$N_F \otimes D_{\gamma/q}$$

away side: $\theta \rightarrow \pi$



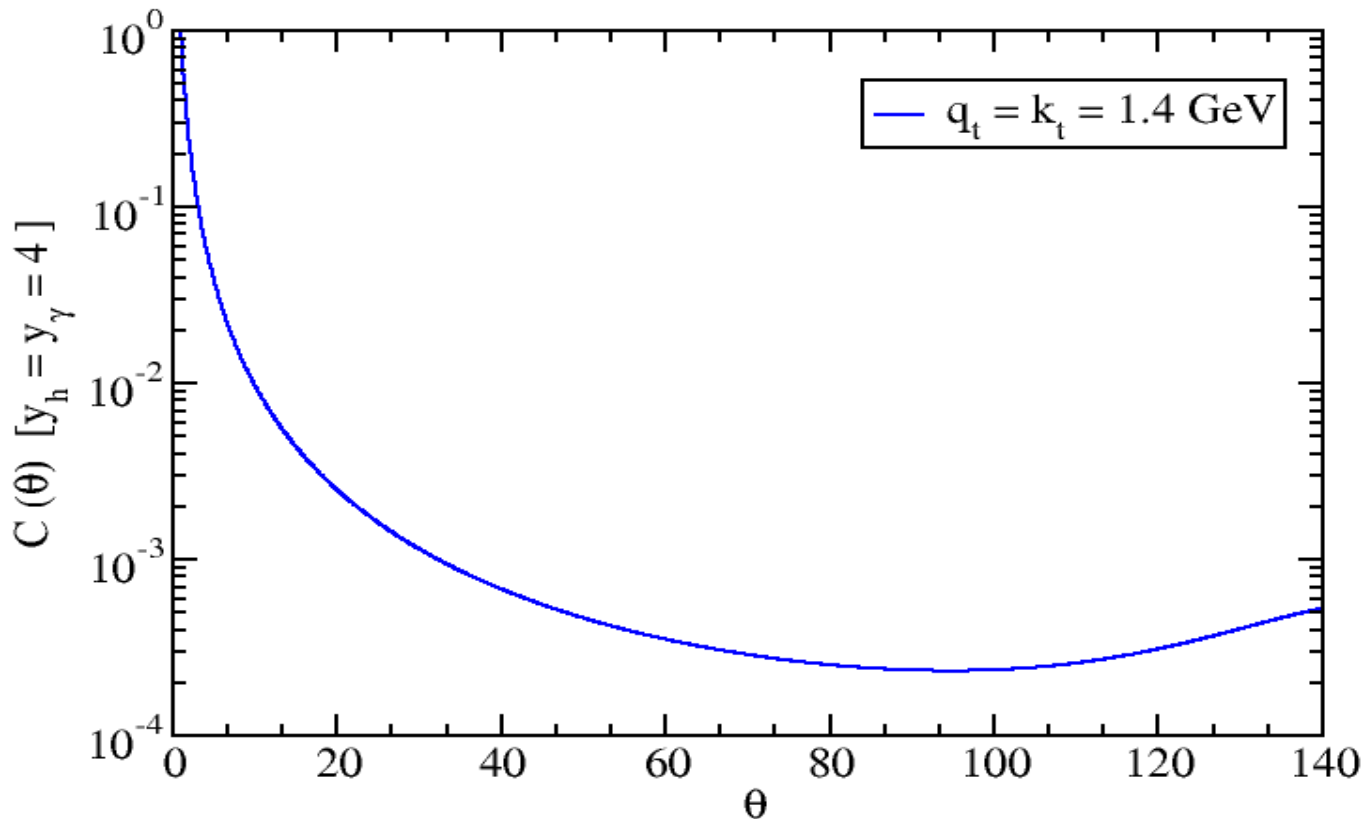
$$p_t \gg Q_s$$

Photon-Hadron correlations:dA



$$C(\theta) \equiv \frac{d\sigma}{dq_t^2 dk_t^2 dy_h dy_\gamma d\theta} \bigg/ \int d\theta \frac{d\sigma}{dq_t^2 dk_t^2 dy_h dy_\gamma d\theta}$$

Photon-Hadron correlations:dA



the code is running!

limited phase space

Summary

Color Glass Condensate: strong field regime of QCD

Plenty of evidence for CGC at RHIC

multiplicities

single inclusive hadron production in dA

Electromagnetic signatures

prompt photons, dileptons in dA

Less inclusive measurements: correlations

two hadrons

photon-hadron